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LISA Pathfinder: Understanding DWS noise performance for the LISA mission

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LISA Pathfinder: Understanding DWS noise performance for the LISA mission

Lennart Wissel on behalf of the LPF collaboration
Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstraße 38, 30167 Hannover, Germany

E-mail: `lennart.wissel@aei.mpg.de`

Abstract. ESA's L3 Laser Interferometer Space Antenna (LISA) mission contains a mechanism to compensate for out-of-plane angles between the received and emitted beams of the three satellites. Depending on the configuration of this Point-Ahead Angle Mechanism (PAAM) it is expected to contribute readout noise through Differential Wavefront Sensing (DWS). This was investigated with LISA Pathfinder (LPF) through a dedicated investigation. One of the two free-falling test masses was rotated via the on-board electrostatic actuators while the resulting angular noise in the differential interferometer between the two test masses was measured. For angles between $-250\,\mu$rad to $250\,\mu$rad and corresponding contrast in the range of $59.4\,\%$ to $97.9\,\%$ an increased spectral density was found. The differential displacement noise remains almost unchanged for these misalignments.

1. Introduction

The performance of LPF's Optical Metrology System is about two orders of magnitude better than the requirement and is subject to ongoing investigations throughout the mission [1]. Differential Wavefront Sensing (see [2]) as a part of this subsystem is used to control four out of six angular degrees-of-freedom of the two test masses. Conceptually, the segments of Quadrant-Photodiodes (QPD) are demodulated to compare the relative phase difference between the wavefronts of the interfering measurement and reference beams for a group of two complementary quadrants. After processing all four channels using a Single-Bin Discrete Fourier Transformation (SBDFT) the resulting complex values, F, contain the encoded phase information which can be retrieved by subtracting left, right and up, down quadrants according to

$$\begin{aligned} \mathrm{DWS}^{\phi} &= \arg\left(F^{\mathrm{left}}\right) - \arg\left(F^{\mathrm{right}}\right), \\ \mathrm{DWS}^{\eta} &= \arg\left(F^{\mathrm{up}}\right) - \arg\left(F^{\mathrm{down}}\right), \end{aligned} \tag{1}$$

during which the equally distributed longitudinal phase is cancelling and the angular phase difference remains. These raw phase measurements can be expressed as equivalent test mass angles $\phi_i, \eta_i; i \in \{1,2\}$ over a linear range of at least $-100\,\mu$rad to $100\,\mu$rad. To calibrate from phase differences to test mass angles, on-ground measurements were performed to determine the coupling coefficients and they are applied as calibration factors in the Data Management Unit (DMU) aboard LPF.

While the digitisation process has a sampling frequency of 50 kHz, further downsampling (to 10 Hz) is applied before transmitting the data to ground. This 10 Hz data is also used to drive the Drag-Free and Attitude Control System (DFACS), keeping the three body system as free from spurious forces as possible.

In the high frequency regime of the DWS data, a quasi-flat noise floor can be observed, as shown in figure 1, allowing a specific noise estimation. In LISA, non-vanishing DWS signals (depending on the point ahead configuration) will originate from motion between the three spacecrafts in combination with their long arm lengths. Beam tilts are magnified by the telescope, causing relatively large DWS phase differences on the quadrants. This distorts the phase readout in a certain way that is investigated here.

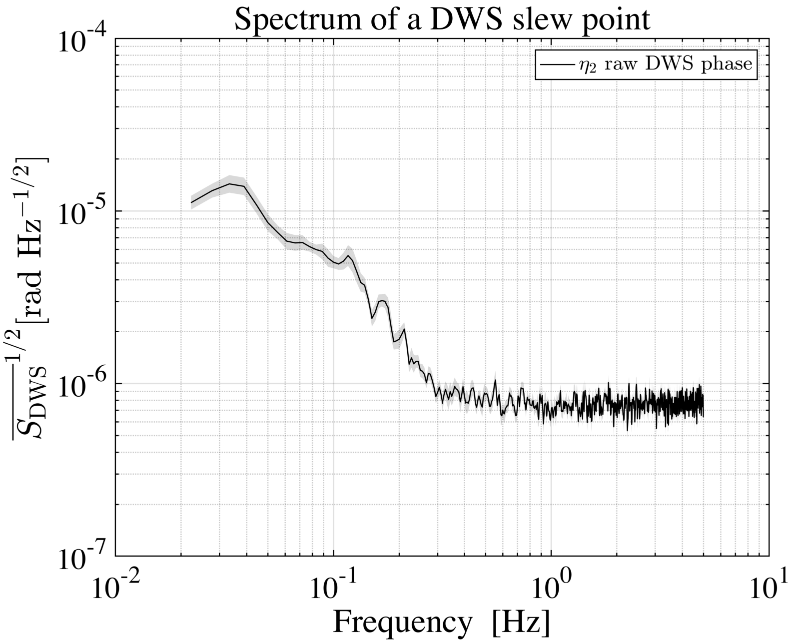

Figure 1. DWS spectral density for a specific offset, showing the high frequency flat noise floor. Below 300 mHz real test mass motion is dominating the spectrum.

2. The DWS step experiment

The DWS step experiment has been designed to measure the DWS noise behaviour and its positional dependence. For this, the electrostatic controllers are used to rotate test mass two around its y and z axes. Motivation for this investigation arises from the following observations: The test mass alignment along ϕ_1, η_1, ϕ_2 and η_2 does not only couple into the differential length measurement given by the x12 interferometer, it has also shown a different DWS noise floor for each of the angular set points that were commanded during the mission. The experiment is designed to quantify different noise levels and investigate their coupling. It assesses the phase noise in the DWS readout regarding its amplitude and phase (or positional) dependence, estimates possible noise sources and coupling mechanisms, allows to fit contrast models related to test mass slews and helps to draw conclusions for requirements on the LISA point-ahead setup.

2.1. Conception

The basic idea consists of commanding a set of angular test mass offsets via the electrostatic controller and calculating the resulting amplitude spectral noise density for each of the steps. LISA Pathfinder has proven to be quiet enough to reach a quasi-flat noise floor within the high frequency regime in the angular test mass readout, where no test mass motion is believed to be happening. For the slews test mass two was chosen because of its closer position to the photodiodes, thus minimizing any induced beam spot offset on the surface of the quadrants. Another benefit is that the differential interferometer is less susceptible to environmental disturbances. The somewhat randomly chosen test mass tilts are shown in figure 2. Larger tilts are not easily possible due to spacecraft safety regulations.

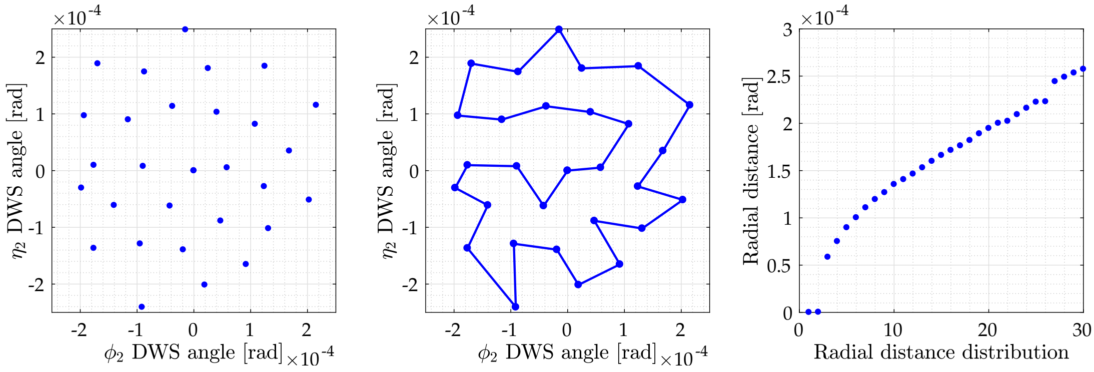

Figure 2. The commanded test mass two tilts are shown in the ϕ_2, η_2 parameter space. All points are randomly placed such that the maximum radial distance is smaller than 260 μrad. The middle plot shows the shortest connecting path of all points, calculated by a travelling salesman algorithm (courtesy of G. Heinzel). It reduces test mass trajectories between set points and the risk of larger overshoots.

2.2. In-orbit behaviour

The experiment was run on DOY 154 (day-of-year) during the mission. In figure 3 the resulting time series can be found. Shown is the angular readout (DWS) and the differential interferometer readout. Every step with a total duration of 45 min is reached in less than 30 min until the rotational degree of freedom stabilizes. In comparison tilt-to-length coupling in x12 motion, introduced by the commanded torques, experiences a slower impulse response of the suspension

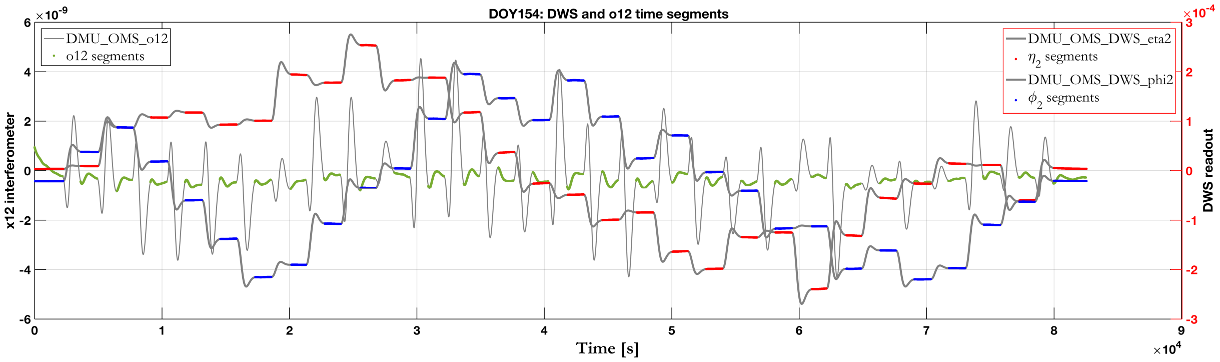

Figure 3. Time series of the measured slews in the DWS step experiment.

controller. Every set point shows an overshoot of various length, when the test mass rotates further than it should, due to the relatively high slew velocities that the controller can not quickly reduce. The maximal overshoot is just below 30 μrad in η_2. The analysis shows a different amplitude spectral density for every set-point. It increases for larger misalignments, i.e. larger phase differences on the measurement diodes.

3. Outlook

Models are used in the ongoing analysis to find the coupling parameters, which are believed to introduce Relative Intensity Noise (RIN) from the laser. A subsequent investigation was run during the mission extension, incorporating much larger slews while also compensating beamwalk effects with parallel commanded test mass one tilts. A publication with the results is in preparation.

4. Acknowledgments

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